Last Time: Vectors + Operations

Dot Product.

Prop (Properties of Vector Addition): Let $\vec{u}, \vec{v}, \vec{w} \in \mathbb{R}^n$
and let $b, c \in \mathbb{R}$.

① $\vec{0} + \vec{u} = \vec{u}$ ← zero vector is the identity for vector addition

pf: $(0, 0, \cdots, 0) + (u_1, u_2, \cdots, u_n)$

$= (0+u_1, 0+u_2, \cdots, 0+u_n) = (u_1, u_2, \cdots, u_n)$ ☑

② $\vec{u} + \vec{v} = \vec{v} + \vec{u}$ ← commutativity of vector addition.

pf: $(u_1, u_2, \cdots, u_n) + (v_1, v_2, \cdots, v_n)$

$= (u_1 + v_1, u_2 + v_2, \cdots, u_n + v_n)$

$= (v_1 + u_1, v_2 + u_2, \cdots, v_n + u_n)$

$= (v_1, v_2, \cdots, v_n) + (u_1, u_2, \cdots, u_n)$ ☑

③ $\vec{u} + (\vec{v} + \vec{w}) = (\vec{u} + \vec{v}) + \vec{w}$ ← vector addition is associative.

pf: $(u_1, u_2, \cdots, u_n) + \Big((v_1, v_2, \cdots, v_n) + (w_1, w_2, \cdots, w_n) \Big)$

$= (u_1, u_2, \cdots, u_n) + (v_1 + w_1, v_2 + w_2, \cdots, v_n + w_n)$

$= \Big(u_1 + (v_1 + w_1), u_2 + (v_2 + w_2), \cdots, u_n + (v_n + w_n) \Big)$

$= \Big((u_1 + v_1) + w_1, (u_2 + v_2) + w_2, \cdots, (u_n + v_n) + w_n \Big)$

$= (u_1 + v_1, u_2 + v_2, \cdots, u_n + v_n) + (w_1, w_2, \cdots, w_n)$

$= \Big((u_1, u_2, \cdots, u_n) + (v_1, v_2, \cdots, v_n) \Big) + (w_1, w_2, \cdots, w_n)$ ☑

④ $c(\vec{u} + \vec{v}) = c\vec{u} + c\vec{v}$ ← (scalar multiplication distributes over vector addition)

pf: $c\Big((u_1, u_2, \cdots, u_n) + (v_1, v_2, \cdots, v_n) \Big)$

$$= c(u_1 + v_1, u_2 + v_2, \cdots, u_n + v_n)$$

$$= \big(c(u_1 + v_1), c(u_2 + v_2), \cdots, c(u_n + v_n) \big)$$

$$= (cu_1 + cv_1, cu_2 + cv_2, \cdots, cu_n + cv_n)$$

$$= (cu_1, cu_2, \cdots, cu_n) + (cv_1, cv_2, \cdots, cv_n)$$

$$= c(u_1, u_2, \cdots, u_n) + c(v_1, v_2, \cdots, v_n) \qquad \boxed{}$$

⑤ $(b+c)\vec{u} = b\vec{u} + c\vec{u}$ ← ("Scalars act on vectors")

pf: $(b+c)(u_1, u_2, \cdots, u_n)$

$$= \big((b+c)u_1, (b+c)u_2, \cdots, (b+c)u_n \big)$$

$$= (bu_1 + cu_1, bu_2 + cu_2, \cdots, bu_n + cu_n)$$

$$= (bu_1, bu_2, \cdots, bu_n) + (cu_1, cu_2, \cdots, cu_n)$$

$$= b(u_1, u_2, \cdots, u_n) + c(u_1, u_2, \cdots, u_n) \qquad \boxed{}$$

⑥ $0\vec{u} = \vec{0}$ and $1\vec{u} = \vec{u}$ ← 0 and 1 act right...

pf: $0(u_1, u_2, \cdots, u_n) = (0u_1, 0u_2, \cdots, 0u_n) = (0, 0, \cdots, 0)$

$$1(u_1, u_2, \cdots, u_n) = (1u_1, 1u_2, \cdots, 1u_n) = (u_1, u_2, \cdots, u_n) \quad \boxed{}$$

Recall: For $\vec{u}, \vec{v}, \vec{w} \in \mathbb{R}^n$ and $c \in \mathbb{R}$:

① $\vec{u} \cdot \vec{v} = \vec{v} \cdot \vec{u}$
   Commutativity

② $\vec{u} \cdot (\vec{v} + \vec{w}) = \vec{u} \cdot \vec{v} + \vec{u} \cdot \vec{w}$
   dot product distributes over vector addition

③ $c(\vec{u} \cdot \vec{v}) = (c\vec{u}) \cdot \vec{v} = \vec{u} \cdot (c\vec{v})$
   linearity

④ $\vec{0} \cdot \vec{u} = 0$
   zero absorption

⑤ $|\vec{u}|^2 = \vec{u} \cdot \vec{u}$
   Norm-Squared law

Algebraic properties of the Dot Product.

Prop (Cauchy-Schwarz Inequality): Let $\vec{u}, \vec{v} \in \mathbb{R}^n$.

Then $\qquad |\vec{u} \cdot \vec{v}| \leq |\vec{u}||\vec{v}|$

Pf: $0 \leq \big| \, |\vec{v}|\vec{u} - |\vec{u}|\vec{v} \, \big|^2 \quad \leftarrow$

$$= \big(|\vec{v}|\vec{u} - |\vec{u}|\vec{v}\big) \cdot \big(|\vec{v}|\vec{u} - |\vec{u}|\vec{v}\big) \quad \leftarrow$$

$$= \big(|\vec{v}|\vec{u} - |\vec{u}|\vec{v}\big) \cdot |\vec{v}|\vec{u} - \big(|\vec{v}|\vec{u} - |\vec{u}|\vec{v}\big) \cdot |\vec{u}|\vec{v}$$

$$= |\vec{v}|\vec{u} \cdot |\vec{v}|\vec{u} - |\vec{u}|\vec{v} \cdot |\vec{v}|\vec{u} - |\vec{v}|\vec{u} \cdot |\vec{u}|\vec{v} + |\vec{u}|\vec{v} \cdot |\vec{u}|\vec{v}$$

$$= |\vec{v}|^2\underbrace{(\vec{u}\cdot\vec{u})}_{|\vec{u}|^2} - \underbrace{|\vec{u}||\vec{v}|(\vec{v}\cdot\vec{u}) - |\vec{v}||\vec{u}|(\vec{u}\cdot\vec{v})} + |\vec{u}|^2\underbrace{(\vec{v}\cdot\vec{v})}_{|\vec{v}|^2}$$

$$= 2|\vec{u}|^2|\vec{v}|^2 - 2|\vec{u}||\vec{v}|(\vec{u}\cdot\vec{v})$$

$$= \underline{2|\vec{u}||\vec{v}|\big(|\vec{u}||\vec{v}| - \vec{u}\cdot\vec{v}\big)} \quad \leftarrow$$

On the other hand $2|\vec{u}||\vec{v}| > 0$, So $|\vec{u}||\vec{v}| - \vec{u}\cdot\vec{v} > 0$.

Hence $\qquad \vec{u}\cdot\vec{v} \leq |\vec{u}||\vec{v}| \qquad$ as desired $\boxtimes$

Remark: I skipped the case $2|\vec{u}||\vec{v}| = 0$, because this implies either $|\vec{u}| = 0$ or $|\vec{v}| = 0$ (and thus $\vec{u} = \vec{0}$ or $\vec{v} = \vec{0}$).

Prop (Triangle Inequality):

$\qquad$ If $\vec{u}, \vec{v} \in \mathbb{R}^n$, then $\quad |\vec{u} + \vec{v}| \leq |\vec{u}| + |\vec{v}|$.

NB: Let's consider vectors $\vec{u} = (1,2,3)$ and $\vec{v} = (-3,1,0)$.

$|\vec{u}| = \sqrt{\vec{u}\cdot\vec{u}} = \sqrt{1^2 + 2^2 + 3^2} = \sqrt{14}$

$|\vec{v}| = \sqrt{\vec{v}\cdot\vec{v}} = \sqrt{(-3)^2 + 1^2 + 0^2} = \sqrt{10}$

$|\vec{u}+\vec{v}| = |(-2,3,3)| = \sqrt{(-2)^2 + 3^2 + 3^2} = \sqrt{22}$.

Note the triangle inequality says $\sqrt{22} \leq \sqrt{14} + \sqrt{10}$ $\boxtimes$

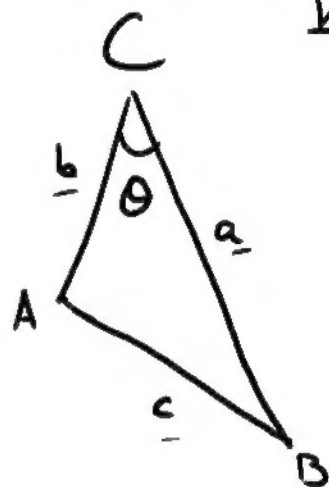pf: Let $\vec{u}, \vec{v} \in \mathbb{R}^n$ be arbitrary

we have

$$|\vec{u} + \vec{v}|^2 = (\vec{u} + \vec{v}) \cdot (\vec{u} + \vec{v})$$
$$= (\vec{u} + \vec{v}) \cdot \vec{u} + (\vec{u} + \vec{v}) \cdot \vec{v}$$
$$= \vec{u} \cdot \vec{u} + \vec{v} \cdot \vec{u} + \vec{u} \cdot \vec{v} + \vec{v} \cdot \vec{v}$$
$$= \vec{u} \cdot \vec{u} + 2(\vec{u} \cdot \vec{v}) + \vec{v} \cdot \vec{v}$$
$$= |\vec{u}|^2 + 2(\vec{u} \cdot \vec{v}) + |\vec{v}|^2$$
$$\leq |\vec{u}|^2 + 2|\vec{u}||\vec{v}| + |\vec{v}|^2$$
$$= (|\vec{u}| + |\vec{v}|)^2$$

Hence $0 \leq |\vec{u} + \vec{v}|$ yields $|\vec{u} + \vec{v}| \leq |\vec{u}| + |\vec{v}|$ as desired. ✓

Recall: Law of Cosines:

Suppose a triangle has

$$c^2 = a^2 + b^2 - 2ab \cos(\theta)$$

Prop (Angle Formula): Suppose $\vec{u}, \vec{v} \in \mathbb{R}^n$ are at angle θ. Then $\vec{u} \cdot \vec{v} = |\vec{u}||\vec{v}| \cos(\theta)$.

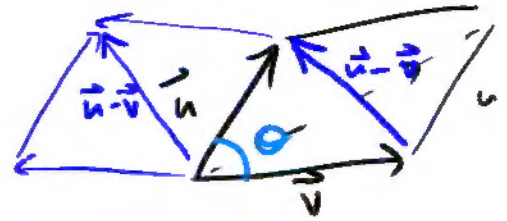Remark: Typically we use this formula to compute the angle θ; in particular:

$$\cos \theta = \frac{\vec{u} \cdot \vec{v}}{|\vec{u}||\vec{v}|} \qquad \therefore \quad \theta = \arccos\left(\frac{\vec{u} \cdot \vec{v}}{|\vec{u}||\vec{v}|}\right)$$

$\cos^{-1}$ ← Sometimes

WTS: $\vec{u} \cdot \vec{v} = |\vec{u}||\vec{v}| \cos(\theta)$ Have: Law of Cosines.

pf: Let $\vec{u}, \vec{v} \in \mathbb{R}^n$ be arbitrary.

$$|\vec{u} - \vec{v}|^2 = (\vec{u} - \vec{v}) \cdot (\vec{u} - \vec{v})$$

$$= (\vec{u} - \vec{v}) \cdot \vec{u} - (\vec{u} - \vec{v}) \cdot \vec{v}$$

$$= \vec{u} \cdot \vec{u} - \vec{v} \cdot \vec{u} - \vec{u} \cdot \vec{v} + \vec{v} \cdot \vec{v}$$

$$= |\vec{u}|^2 - \vec{v} \cdot \vec{u} - \vec{u} \cdot \vec{v} + |\vec{v}|^2$$

$$= |\vec{u}|^2 + |\vec{v}|^2 - 2(\vec{u} \cdot \vec{v})$$

On the other hand, by the Law of Cosines,

$$|\vec{u} - \vec{v}|^2 = |\vec{u}|^2 + |\vec{v}|^2 - 2|\vec{u}||\vec{v}|\cos(\theta)$$

Hence $|\vec{u}|^2 + |\vec{v}|^2 - 2(\vec{u} \cdot \vec{v}) = |\vec{u}|^2 + |\vec{v}|^2 - 2|\vec{u}||\vec{v}|\cos(\theta)$,
So we can rearrange this formula to become

$$\vec{u} \cdot \vec{v} = |\vec{u}||\vec{v}| \cos(\theta)$$ as desired. ☑